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JUNO ORBIT DETERMINATION EXPERIENCE DURING FIRST YEAR AT JUPITER[†]

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The Juno spacecraft successfully inserted into a polar orbit around Jupiter on 5-July-2016. Since the Jupiter Orbit Insertion (JOI) maneuver, Juno has completed six orbits around Jupiter. The mission plan at the time of JOI was for Juno to perform two 53.5-day capture orbits before executing a Period Reduction Maneuver (PRM) to place the spacecraft into its intended 14-day science orbit. This maneuver was canceled due to a concern with the propulsion system. As a result, the Juno spacecraft will remain in its longer orbit period for rest of its mission. This paper discusses the Navigation Team's experience: the orbit determination strategy and how it changed due to the cancellation of the PRM, challenges fitting the data during perijove, and how we reconstructed the trajectory during Juno's first year in orbit.

INTRODUCTION

Following a five-year journey that began with its launch on 5-August-2011, Juno successfully entered into polar orbit around Jupiter on 5-July-2016. The 35-min Jupiter Orbit Insertion (JOI) burn placed Juno into a 53.5-day capture orbit. At the time of JOI, the mission plan was for Juno was to execute a Period Reduction Maneuver (PRM) after two capture orbits. PRM was meant to decrease the orbital period from 53.5 days to 14 days, thus allowing Juno to complete 20 orbits in its first year. However due to concerns with the propulsion system's main engine check-valve, PRM was delayed and ultimately canceled. From JOI through 19-May-2017, Juno completed six 53-day orbits yielding unexpected science results and unprecedented views of Jupiter's poles. It is the Project Management's goal to still perform the 36 orbits of Jupiter originally intended past the prime mission end date in February 2018, all the way through July 2021.

The main objective of the Navigation (Nav) Team, consisting of trajectory design, orbit determination (OD), and maneuver design, is to keep Juno on the designed reference trajectory in order to hit the longitude target for each successive equator-crossing near perijove (PJ). Maneuvers after each perijove are required to target the radius and longitude of subsequent perijove. As such, the OD team's primary function is to process tracking data in order to reconstruct and predict the spacecraft trajectory for maneuver design and science planning. Around the time of the subsequent apojove (AJ), the OD team delivers an official reconstruction of Juno's as-flown trajectory relative to the Jupiter barycenter for the preceding orbit, with particular focus on the trajectory during the previous perijove for better analysis of the collected science

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data. In the following sections, we give an overview of the Juno spacecraft and its orbital mission to provide context for the Nav team's role, detail the impact of PRM's cancellation on the OD team, and discuss the OD team's use of radiometric data to reconstruct the six perijoves and the challenges each perijove posed.

JUNO SPACECRAFT

Like its forerunner Galileo, Juno is a spin-stabilized spacecraft. However, Galileo was a dual-spinner in order to accommodate a non-rotating scan-platform for its remote sensing instruments, as well as a spinning section for the fields and particle instruments. Juno is a single-spinner, without a separate scan-platform. Another significant difference between Galileo and Juno, and really every other spacecraft sent to the outer planets to date, solar arrays rather than radioisotope thermoelectric generators power the spacecraft. The solar arrays need to be quite large in order to generate the required power for Juno over 5-au away from the Sun. With nearly 60 square-meters of solar arrays along three 8.7-meter long wings generating about 450 Watts, Juno is the farthest spacecraft from the Sun to completely operate on solar power (see Figure 1).

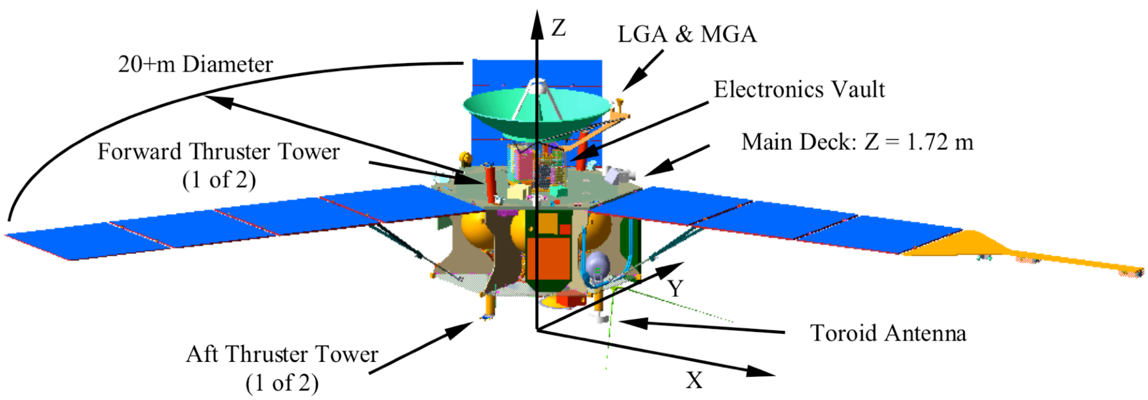

Figure 1. Juno spacecraft.

Juno rotates counter-clockwise about the positive Z-axis, which is aligned with the High Gain Antenna (HGA). The HGA is Juno's primary communications antenna, as the spacecraft is almost always pointed at Earth. The Medium Gain Antenna (MGA) is occasionally used during specifically designated perijoves when the spacecraft needs to be pointed away from Earth and while the spacecraft is pointed at Earth during Orbit Trim Maneuvers (OTM) in order for the Deep Space Network (DSN) antenna to maintain communications lock. Juno's nominal spin rate since JOI has been 2 rpm.

Juno has a dual mode propulsion system: a single bi-propellant main engine (ME) and three monopropellant reaction control system (RCS) thrusters on each of the four thruster towers. The 663-Newton ME was used for the two Deep Space Maneuvers (DSM) and JOI. With the cancelation of PRM, there are no plans to use the ME for the rest of the mission. The suite of 4.5-Newton RCS thrusters is used on a regular basis to reorient the HGA back towards Earth as it moves away from Juno's spin axis. The RCS thrusters are also used for OTMs and spin-rate control.

JUNO MISSION OVERVIEW

Juno was launched in August 2011 aboard an Atlas V launch vehicle. After the two DSMs in August and September 2012 and an Earth flyby gravity assist in October 2013, Juno finally reached Jupiter on 5-July-2016 with JOI placing the spacecraft into a 53.5-day polar orbit. The OD results from the Earth flyby and JOI are reported by Thompson, et al. (2014, 2017)[1,2]

While in this unique orbit around Jupiter, Juno's science goals include determining the mass and composition of Jupiter's core, investigating the abundance of water, ammonia, and heavy elements in Jupiter's atmosphere, exploring the structure of Jupiter's atmosphere, and detailed mapping of the gravity and magnetic fields. Through our continued efforts to study the origin and evolution of the first planet formed in our solar system, the science community hopes to not only improve their understanding of our solar system, but also the many planetary systems being discovered around other stars.[3]

The Nav team's responsibility to help achieve Juno's science objectives is to maintain Juno's reference trajectory by hitting the longitude targets for each respective equator crossing near perijove. The reference trajectory is specifically designed to build a web of evenly spaced longitude crossings around Jupiter's equator to provide global coverage over the course of the mission, as notionally illustrated in Figure 2. The OD team's role in this aspect of the mission is to deliver accurate predicted trajectories to the Maneuver team for their design of maneuvers to aim for designated equator-crossing longitude targets.

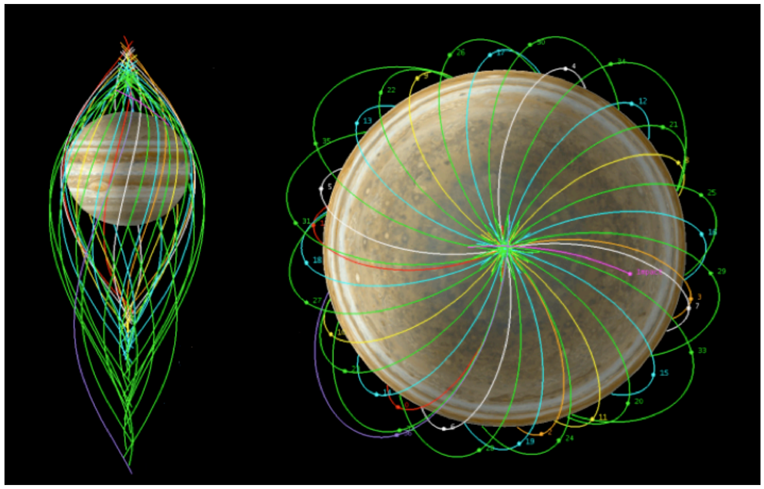

Figure 2. Juno's Orbital Net Around Jupiter (shown in Jupiter-centered, Jupiter-fixed frame)

At the time of JOI, the mission design was for Juno to perform two 53.5-day capture orbits. The first perijove that occurred on 27-August-2016 (i.e., PJ01) gave the science teams an opportunity to checkout their instrument operations procedures in Jupiter's intense radiation environment. The longitude for PJ01 was targeted by a successfully executed a JOI-cleanup maneuver. After a flawless science encounter at PJ01, and soon after exiting solar conjunction, the spacecraft was set to execute its PRM at PJ02 on 19-October-2016 and then a PRM-cleanup maneuver 14 days later at PJ03 on 2-November-2016. For the remainder of the prime mission, the spacecraft and its mission operation team were to be on a regular cadence of extensive data collection ±3 hours around every perijove and an OTM four to 7.5 hours after each perijove to target the longitude for the next perijove.[4]

While preparing the propulsion system for PRM, a concern surfaced. During tank pressurization a week before PRM, the helium check-valves took longer than expected to open. "Sticky" check valves have been seen by other spacecraft, including (and coincidentally) on the last spacecraft to orbit Jupiter, Galileo.[5] PRM was delayed upon discovery of this anomaly and the propulsion system's reliability was thoroughly investigated by the project. Even though exercising the helium check-valve during a pressure-regulated maneuver was deemed unsafe for any future PRM, the prospect to possibly perform PRM in blow-down mode was considered. An unregulated "blow-down PRM" would have resulted in less thrust and the resulting reduction in the achieved delta-V would have placed Juno in a 20-27 day orbit.[6] In order to provide sufficient time for the various teams to perform their trade studies for the various trajectory options, the project decided that any possible PRM would not occur before PJ06 on 19-May-2017.

The impact to remain in the 53-day orbit was of course felt within each team and subsystem of the project. From the standpoint of OD, additional deliveries were required to support: 1) longer spacecraft background sequences of commands generated by the Spacecraft Team (SCT); 2) additional deterministic maneuvers around apojove (referred to as APO maneuvers) as needed in order to optimize propellant usage for targeting the next equator-crossing longitude and controlling PJ radius; and 3) new statistical trim maneuvers (STM) to cleanup and OTM or APO execution errors, as needed. Figure 3 provides a notional illustration of the current maneuver strategy and the data cutoff (DCO) to support the additional deliveries from OD. As noted in Figure 3, OD deliveries for all maneuvers are made about one week before maneuver execution. This gives the SCT team sufficient time to build, test, approve, and uplink the commands necessary to execute the maneuvers.

After about five months of investigation, NASA agreed with the Juno Project recommendation to cancel PRM and keep the spacecraft in a 53-day orbit for the rest of the mission. By this point the changes to the OD process, which were redeveloped during the third orbit and still evolving during the fourth orbit, were becoming more routine in the fifth and sixth orbits. A new data arc strategy was required in order to support the additional OD deliveries, which we discuss in a subsequent section.

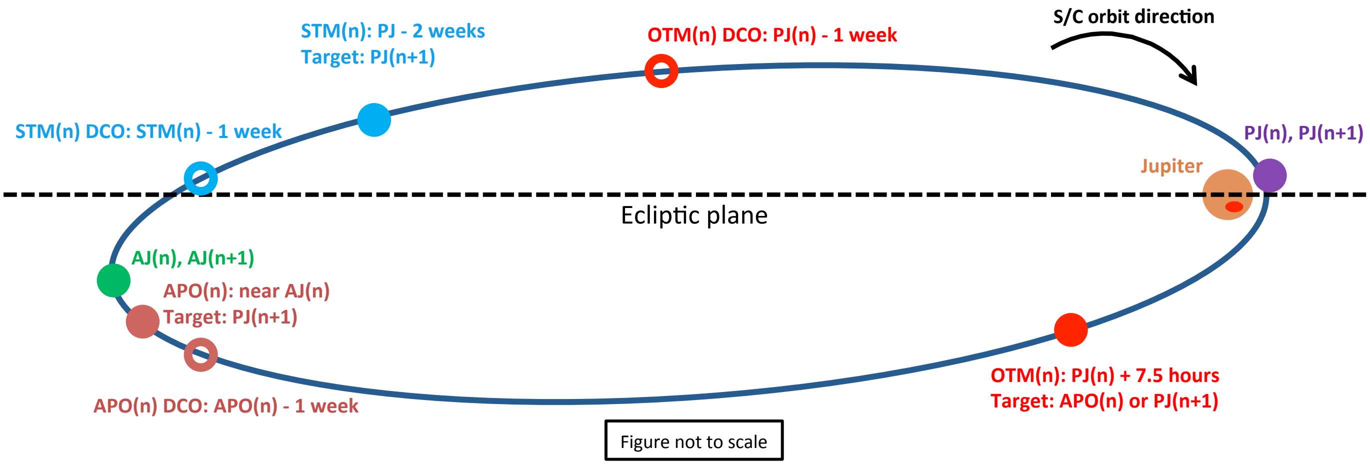

Figure 3. Current Maneuver Strategy and OD Deliveries During Juno's 53-day Orbit

Two types of spacecraft attitudes at perijove

Depending on the primary science objective for each specific perijove, Juno is configured to be dedicated for collecting data for the Gravity Science Team (GRAV) or the Microwave Radiometer Science Team (MWR). Perijoves committed to GRAV are characterized with the spin-axis, and thus the HGA, pointed towards the Earth. For the MWR perijoves, the spin-plane (i.e., the spacecraft X-Y plane) intersects the center of Jupiter so that the MWR instrument field of view rotates though the nadir direction as the spacecraft spins.[3] This configuration requires Juno to be pointed away from Earth during perijove and thus the MGA is used to track the spacecraft by the DSN. Figure 4 illustrates the differences in the spacecraft attitude between GRAV and MWR perijove passes. During Juno's first year in orbit, PJ01, PJ02, PJ05, and PJ06 were "GRAV perijoves" and PJ03 and PJ04 were "MWR perijoves." This difference in attitude and antenna being employed had a significant impact on the OD process, as we discuss later when presenting the OD solution for each respective perijove.

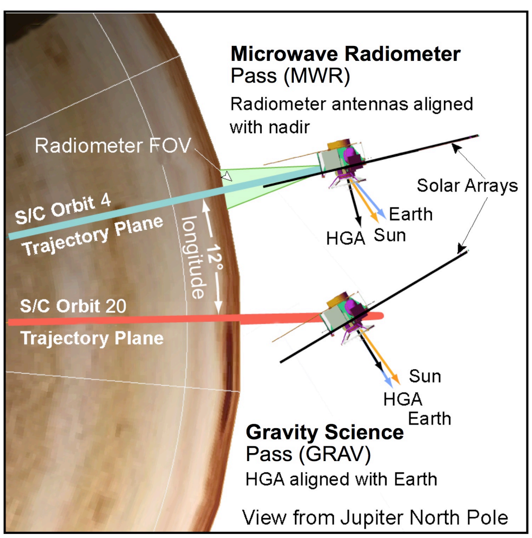

Figure 4. Juno's Attitude During GRAV and MWR Perijove Passes

JUNO ORBIT DETERMINATION SETUP AND MODELING

OD for Juno is accomplished with the Mission-analysis and Operations Navigation Toolkit Environment (MONTE), a navigation software package created at JPL.[7] Orbit parameters, propulsive events, filter measurements, and stochastic parameters are defined in a MONTE environment, and the data are filtered to convergence in order to reconstruct the past trajectory and then propagate the spacecraft's trajectory into the future. Parameters are defined within MONTE by selecting the appropriate model and setting an *a priori* value and associated covariance for each parameter to be estimated within the model.

Radiometric data acquired by the DSN that were used to estimate these parameters include 2-way coherent Doppler and 2-way range measurements. A minimum horizon cutoff elevation of 10-deg was imposed at the DSN on the radiometric data. Doppler data was weighted on a per-pass basis to the standard deviation of the post-fit residuals, multiplied by a scale factor of 3.36 to account for noise due to solar plasma. The minimum weight corresponds to 0.05-mm/s. Range data was weighted such that the effective per pass weight was 5-m. Delta-differential One-way Range (DDOR) was used throughout the JOI campaign and afterwards to better resolve Juno's trajectory post-JOI for the design of JOI-cleanup maneuver. DDOR measurements, weighted at 0.06-ns, were taken up until one week before PJ01 on 20-August-2016. None of the orbits after PJ01 discussed in this paper contained DDOR measurements. Variability of the Earth's ionosphere and troposphere were measured and used to apply corrections to the radiometric and DDOR data.

Every 399 days solar conjunction between Earth and Jupiter occurs. Radio signals passing close to the Sun are affected by the solar plasma charged particles. During this period Doppler and range data are deweighted to the equivalent of 1-mm/s and 100-m respectively once the Sun-Earth-Probe (SEP) angle goes below 15-deg. At SEP angles below 7.5-degree the Doppler is further deweighted at 5-mm/s and the range data is ignored. All radiometric data is removed when SEP angles are 3-degrees or less.

The dynamic models used to propagate the spacecraft trajectory include the gravitational attraction from the Sun, the Moon, the eight planets, Pluto, and the Galilean satellites; solar radiation pressure (SRP); small force events; and spacecraft maneuvers. The SRP is modeled using multiple spacecraft plates: a two-sided plate for the entire solar panel area, a two-sided plate for the magnetometer boom attached at the end of one of the solar panels, and a one-sided plate for the cap on the +Z side of bus. The bus itself is modeled as a cylinder. Surface properties (specular and diffuse coefficients) were calibrated based on flight experience soon after launch.

Small force events associated with spacecraft turns and spin rate corrections are modeled as instantaneous impulsive maneuvers. Most spacecraft turns were very small (<0.3-degrees) in order to maintain the HGA pointed at Earth. The only exceptions were for the handful of larger turns required for the MWR perijove passes. Those turns away from Earth-point (and back again) were between 24 and 27-degrees. Spin rate control events are only required when the spin rate error exceeds its deadband limit of ±0.05 rpm from the nominal rate of 2 rpm. Larger thrusting events such as OTMs and APO maneuvers are modeled as finite burns with delta-V magnitude, right ascension, declination, and start time of the burn as estimated parameters.

The OD filter process estimates the initial state of the spacecraft at the epoch of the data arc, and as many as 250 constant bias parameters affected by dynamics or observable data. The vast majority of these estimated bias parameters are for the impulsive delta-V events due to spacecraft turns, as they may occur as frequently as every couple of days. Other parameters estimated every orbit include the magnitude, direction, and start time from one or two finite burn events and a single SRP scale factor that is applied to the total force model. With Juno now at Jupiter, the heliocentric distance is nearly constant, and as such the SRP force has also been nearly constant.

Besides calibrations to ionosphere and troposphere models to correct the radiometric and DDOR measurements, corrections to Earth's rotation and polar motion are also applied to measurement models. Errors due to ionosphere, troposphere, Earth orientation parameters, DSN station locations, quasar locations, Jupiter barycenter ephemeris, Jupiter satellite ephemeris, and Jupiter gravity harmonics are all considered in the OD filter (their uncertainties are included, but the parameters themselves are not estimated). The filtering process does not improve upon the *a priori* uncertainty of these parameters, so they merely contribute uncertainty to the values of the estimated parameters.

Lastly, it is worth noting that ever since JOI, a constant range bias has been estimated throughout each data arc. This constant bias accounts for any line-of-sight range mismodeling, primarily due to error in the Jupiter barycenter ephemeris. The Jupiter barycenter ephemeris is not directly estimated by the filter in the nominal configuration.

Jupiter Barycenter Ephemeris

In preparation for JOI, the Solar System Dynamics group at JPL delivered the DE434 planetary ephemeris to the OD team[8]. It improved upon the DE430 planetary ephemeris mostly though the updated analysis of data from six previous spacecraft flybys and the addition of New Horizons flyby of Jupiter back in 2007.[9] During the approach to JOI, the OD team faced challenges separating errors in the spacecraft trajectory from errors in the Jupiter barycenter ephemeris. A couple days prior to JOI, the OD team was finally convinced that the errors in the predicted spacecraft trajectory were due to errors in the Jupiter barycenter ephemeris. This understanding made it necessary to include an OD-estimated Jupiter barycenter ephemeris with subsequent OD deliveries for JOI reconstruction and maneuver designs through PJ01. The analysis that ultimately led us to this conclusion is well described in detail in Reference 2.

The development of DE434 was performed in conjunction with the development of the satellite ephemerides for the Jupiter system, JUP310.[10] The radiometric data used to help us detect errors in the Jupiter barycenter ephemeris were not sensitive enough to also detect errors in the satellite ephemerides. Therefore, the satellite ephemerides have remained fixed and un-estimated in the OD process.

The Solar System Dynamics group included Juno's first perijove flyby on 27-August-2016 and additional ground observations around the same time to produce the DE436 planetary ephemeris.[††] The correction to the Jupiter barycenter ephemeris relative to DE434 calculated during the reconstruction of Juno's trajectory for the approach to JOI compared very closely to this new DE436 ephemeris.[2] This agreement between the estimated ephemeris of those OD solutions to DE436 gave the OD team greater confidence in switching the default planetary ephemeris to DE436. The OD team no longer estimates the Jupiter barycenter ephemeris as part of the standard solution process.

Despinning Doppler Data

Since Juno is a spinning spacecraft, before the Doppler data can be fit it must be pre-processed in order to remove the spin signature and spin-induced Doppler bias due to antenna polarization. This phenomenon was first observed by Pioneer 10 in 1972 and described mathematically by Berman.[11] The process of removing the spin signature and Doppler bias for Juno is similar to the procedures and scripts originally developed for Mars Science Laboratory (MSL) as documented by Gustafson, et al.[12] Interestingly, Juno was the first operational use of MSL's procedure since Juno launched three months before MSL. Obviously MSL and Juno are two completely different spacecraft designs, but the math and techniques to "despin" the raw Doppler data between the two OD teams are identical. The mass properties and antenna locations (phase centers) are the primary difference between the MSL and Juno "despin process" and thus needed to be specifically defined for Juno. Juno's initial use of the despin tool served as great validation for MSL and the tool worked very well throughout the interplanetary cruise phase of the mission up to the fourth perijove (PJ04). The data characteristics during PJ04, specifically a rapidly changing spin rate, exceeded the capabilities of the despin tool worked and an alternate method had to be developed. This phenomena and the OD team's solution are described in greater detail in the section about PJ04.

Juno's HGA has been used for the majority of the mission. Since the HGA is aligned with the spin axis and the off-Earth angle never exceeded 0.3 degrees, no spin signature is detected by the despin tool and ostensibly the tool just removes the spin-induced Doppler bias. During the interplanetary cruise phase of the mission, there were times where one of the Juno's three other antennas was used, especially when the spin axis spacecraft was not pointed Earth during the inner cruise before Juno's Earth flyby. In those instances, the despin tool did in fact remove the spin signature as well as the induced Doppler bias. While in orbit around Jupiter, there is no plan to use either Low Gain Antenna or Toroidial Antenna ever again. As previously before, the only planned time Juno is pointed away from Earth and is required to use the MGA

[††] Personal communication with W.M. Folkner, JPL, July 2017

is around the time of certain perijoves to enable MWR data collection. Challenges in removing the spin signature during the MWR perijoves and the OD team's solution are discussed in an upcoming section.

In addition to being used during MWR perijove encounters, the MGA is also used during OTM and APO maneuvers. Even though these maneuvers are performed while Juno's spin axis is pointed at Earth, the wider beamwidth of the MGA is used to help ensure the DSN maintains communications lock with Juno in case the execution of the maneuver causes the spacecraft to be pointed more than 0.3-degrees pointed away from Earth. Even though the MGA is offset from the spin axis by about 1.4-m, having the spin axis pointed directly at Earth also results in an undetectable spin signature. Similar to when Juno is using the HGA, removing the induced Doppler bias becomes the primary task of the despin tool. Figure 5 shows the Doppler residuals during the first part of the station-tracking pass before the APO06 maneuver where Juno transition between the HGA and the MGA. As expected, the Doppler residuals from the MGA are noisier than from the HGA (due to the wider beamwidth from the MGA). On the left are the residuals of the raw Doppler data as received by the DSN, which show a bias of about -1.26 mm/s for ~1.96 rpm. Once the raw Doppler data have been "despun" the Doppler data are compressed to a 300-second count time and are ready to be further processed by MONTE (note the zero bias).

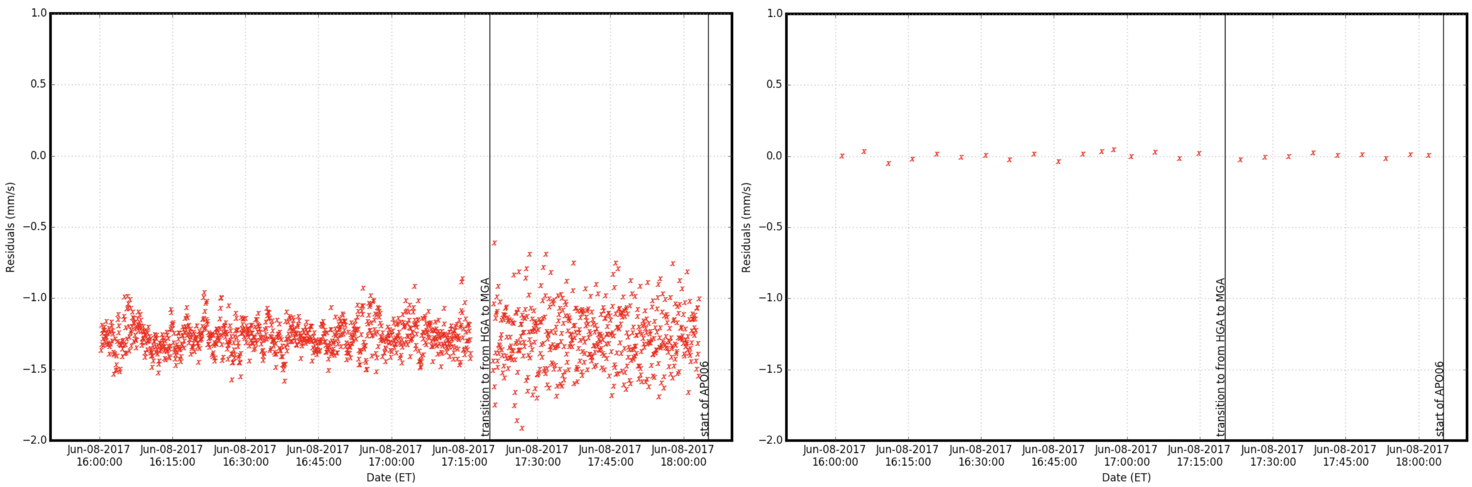

Figure 5. HGA and MGA Doppler Residuals Before (on left) and After (on right) Using Despin Tool to Remove Spin-induced Doppler Bias and Compressing Data from 60-s to 300-s Count Time

Another nuance to despinning the raw Doppler data is that occasionally the predicted trajectory was too far off in order for the despin tool to output acceptable "despun" Doppler data. This typically was after a perijove encounter or after an OTM had executed. Even though the trajectory after those events may have been within the predicted delivery uncertainties, it may have still been far enough off for the despin tool to not be effective. In those cases, a "quick and dirty" OD solution was generated by adjusting the Doppler data for the spin-induced bias manually. If there was a spin signature in the data it would not be accounted for and the data was simply processed as "noisy data." This technique to generate a more accurate trajectory prior to using the despin tool proved to be the best way to ease stress on the tool to provide a valid result.

Data Arc Strategy

A new strategy to establish new orbital data arcs was one of the many changes to the OD process after PRM was canceled. In the previous mission design where Juno's orbital period was 14 days, a new data arc would have started near apojove (AJ_n). The newly created "short arc" would serve as a way to validate the performance of the "long arc." The 13-day old long arc would have been use to deliver OD solutions for OTM development. After the perijove passage and OTM execution eight days later, the long arc would have been retired and the short arc would become the new long arc.

With the long 53-day orbits and as many as two additional maneuvers to support per orbit, the OD team did not feel like the strategy for 14-day orbits would work as well. Specifically, it was deemed imprudent to wait 53 days without having additional data arcs to validate other solutions. Therefore, the OD team decided to initiate data arcs twice per orbit: one after the post-perijove maneuver, OTM_n, and another after the maneuver near apojove, APO_n, but before apojove, AJ_n (see Figure 3 for reference). Both the "perijove" and "apojove" arcs had the epoch start after the maneuver so that the maneuver parameters did not need to be estimated. However, the same uncertainty of the spacecraft velocity could not be used for each of these epochs. For the data arcs that start around after the post-perijove OTM, Juno's Jupiter-relative velocity is on the order of 15 km/s and at apojove the spacecraft's velocity is on the order of 0.6 km/s. A "one-size fits all" setting for the uncertainty was not suitable because either the uncertainty would be so small that the filter would try to treat the *a priori* state at the epoch as "truth" rather than let the data shift it or the uncertainty would be so large that the filter would not know where the spacecraft state was at the epoch. The desire was to set the *a priori* uncertainty of the velocity that allowed the data to determine the spacecraft state, rather than assuming our knowledge of the spacecraft state at the epoch is better than it really is. For the arcs that start near perijove, the *a priori* uncertainty of the velocity is 10 km/s and near apojove it is set to 0.5 km/s. Sensitivity to the *a priori* uncertainty of the spacecraft position for the "apojove arcs" has not been observed. The *a priori* uncertainty of the spacecraft position is set to 50,000 km for both types of data arcs.

RECONSTRUCTION OF PERIJOVE ENCOUNTERS

Figure 8 displays Juno's equator-crossing longitude grid based on the current reference trajectory. The science encounters from Juno's first year at Jupiter are circled. The red circles signify "GRAV perijove encounters" and the green circles signify the "MWR perijove encounters." The only longitude missing on this grid is that of PJ02 because science instruments did not collect any data during that perijove. The following sections discuss the unique details from each of the encounters.

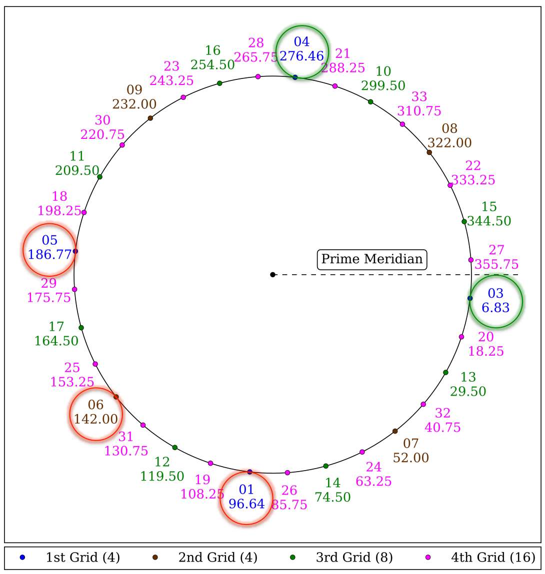

Figure 8. Juno Equator-Crossing Longitude Grid; West Longitude is shown in degrees (encounters from first year are circled: red = "GRAV perijove"; green = "MWR perijove") (PJ02 not a part of equator-crossing longitude grid due to spacecraft "safe mode")

PJ01

Juno's perijove encounter on 27-August-2016 gave the science teams their first opportunity to check out their instruments in the harsh Jovian radiation environment and to tune their operations procedures. This first encounter after JOI was targeted by the JOI-Cleanup maneuver. Maneuver performance was sub-sigma and stable OD solutions enable the cancelation of the statistical OTM00 maneuver.[13]

This close encounter also gave the OD team their first usable radiometric data during a perijove as only 1-way Doppler data was received during JOI. Using 2-way Doppler and range data revealed the effect of errors in Jupiter's gravity field, pole, and barycenter ephemeris on Juno's trajectory. Similar to the experience prior to JOI, errors in the Jupiter barycenter ephemeris were shown to be the greatest error source in the prediction of Juno's trajectory relative to Jupiter coming into the PJ01 close approach. Trajectory prediction deliveries were not required prior to PJ01 in order to design OTM01, which executed 18 days after PJ01 on 14-September-2016.

Fitting the Doppler data during PJ01 was not necessary to produce accurate predicted trajectories following PJ01. The DSN tracks immediately after PJ01 proved to be more crucial for long term predictions than did the data at PJ01. Therefore, to predict the trajectory leading into OTM01, the radiometric data during perijove were ignored. Since DE434 was still being used for the Jupiter barycenter ephemeris, estimation of the Jupiter barycenter ephemeris was still required for OD deliveries supporting the maneuver design of OTM01. As previously mentioned, later the Solar System Dynamics group at JPL delivered the planetary ephemeris DE436 that corrected the ephemeris errors previously observed. As such, DE436 is what was used for this delivery of Juno's trajectory reconstruction, as well as subsequent deliveries of Juno's predicted and reconstructed trajectories.

The greatest challenge to fitting the data around PJ01 was due to Jupiter's gravity harmonics and pole orientation. At first the filter was unable to fit the data around PJ01 at all unless Jupiter's gravity and pole were included in the estimated parameter list. While estimating these parameters enabled the filter to fit the data, the OD team was skeptical of the results because of the relatively long duration of our data arc and the presence of numerous other estimated parameters, including small forces around the time of the perijove. A new gravity model and pole orientation parameters were requested from the Radio Science team based on the OD team's findings. The Radio Science team was able to provide the Navigation team with zonal harmonic values up to degree 8, along with updated pole orientation parameters.[‡‡] These changes aided greatly in fitting the PJ01 Doppler data, yet occasional stochastic accelerations were still required in order for the filter to better fit the Doppler data to mean-zero during the PJ01 tracking-pass.

The residuals for the 2-way Doppler and range measurements for the entire data arc relative to the reconstructed trajectory are shown in Figure 9, with Figure 10 zooming in to show the Doppler residuals around PJ01. Figure 11 presents the OD team's reconstruction of PJ01 (blue ellipse) relative to the targeting maneuver (red ellipse) and relative to the decision to cancel the statistical cleanup maneuver (green ellipse).

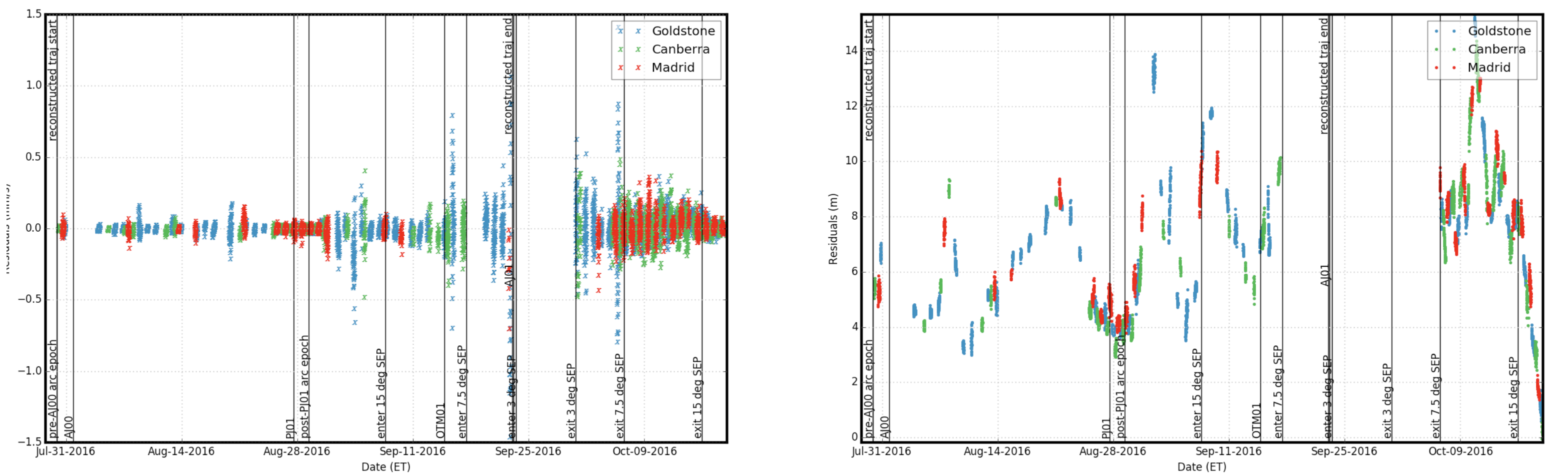

Figure 9. Doppler (right) and Range (left) Residuals During PJ01 Reconstruction Arc

‡‡ Personal communication with M. Parisi, California Institute of Technology, October 2016

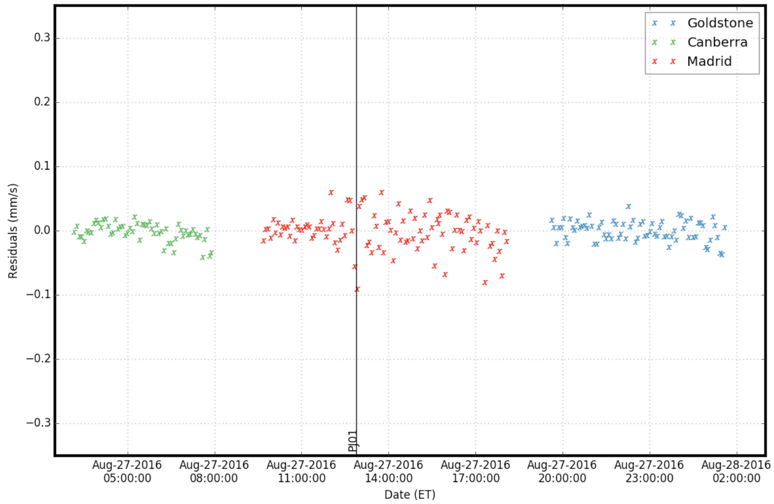

Figure 10. Doppler Residuals around PJ01 Encounter

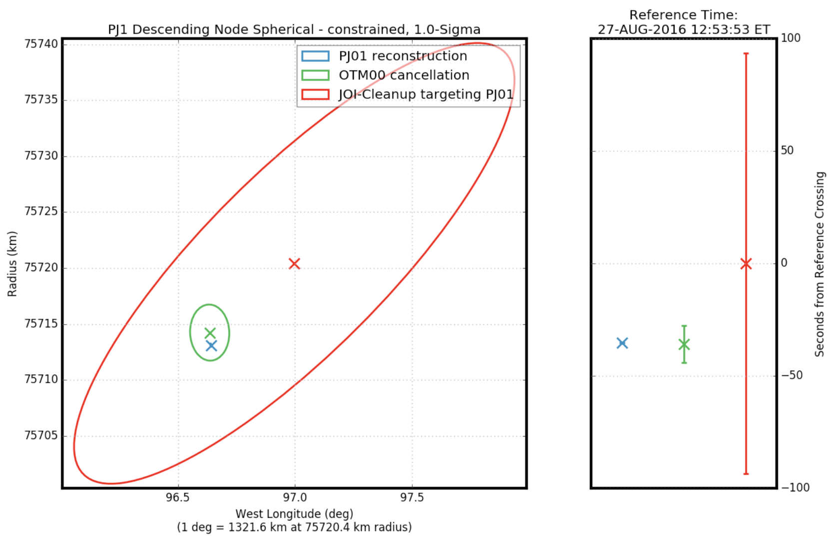

Figure 11. Results of Equator-Crossing from PJ01

PJ02

Originally the PJ02 perijove pass was designated for PRM execution on 19-Oct-2016. The location for PRM was targeted by OTM01 on 14-September-2016, 18 days after PJ01. No statistical cleanup maneuver was planned before PJ02 since a PRM-cleanup maneuver was scheduled at PJ03. When PRM was cancelled, the science instruments were quickly configured for data collection in order to add this equator-crossing longitude to the grid. Unfortunately, the spacecraft went into “safe mode” a few hours before PJ02, resulting in the background sequence being canceled and automatically powering off all the science instruments. These actions precluded any science data from being collected at PJ02. Fortunately, the DSN was able to maintain 2-way lock with the HGA on X-band, and the collection of Doppler allowed the OD team to reconstruct Juno’s trajectory through PJ02.

For the 38 days leading up to PJ02, Juno was near solar conjunction where the Sun-Earth-Probe (SEP) angle was within 15 degrees. PJ02 occurred four days after Juno exited this solar conjunction period. During this period of low SEP angle, radiometric data was either deweighted or completely ignored. This lack of high-quality data hampered the OD team’s ability to precisely estimate the resulting delta-V from the precession turns executed to maintain an Earth-pointed attitude for HGA communications. Additionally, the uncertainty of the trajectory reconstruction during this period was higher than it would otherwise have been if conjunction had not occurred. However, the only requirement for reconstruction deliveries is for the trajectory position uncertainty to be less than 10 km ±3 hours around perijove (1-sigma) and that requirement was met for PJ02.

The residuals for the 2-way Doppler and range measurements for the entire data arc are shown in Figure 12, with Figure 13 zooming in to show the Doppler residuals around PJ02. Upon request from the OD team, the Radio Science team provided another refinement to their gravity model in order to help better fit the Doppler data. Stochastic accelerations were also used again during the perijove tracking-pass to account for any mismodeling in the gravity model. Solutions using compressed and uncompressed Doppler data around PJ02 were examined. The trajectory reconstruction using the uncompressed data was delivered because it fit the Doppler data through PJ02 better than the compressed case.

Figure 14 presents the OD team's reconstruction of PJ02 (blue ellipse) relative to the targeting maneuver (red ellipse). There was no the statistical cleanup maneuver.

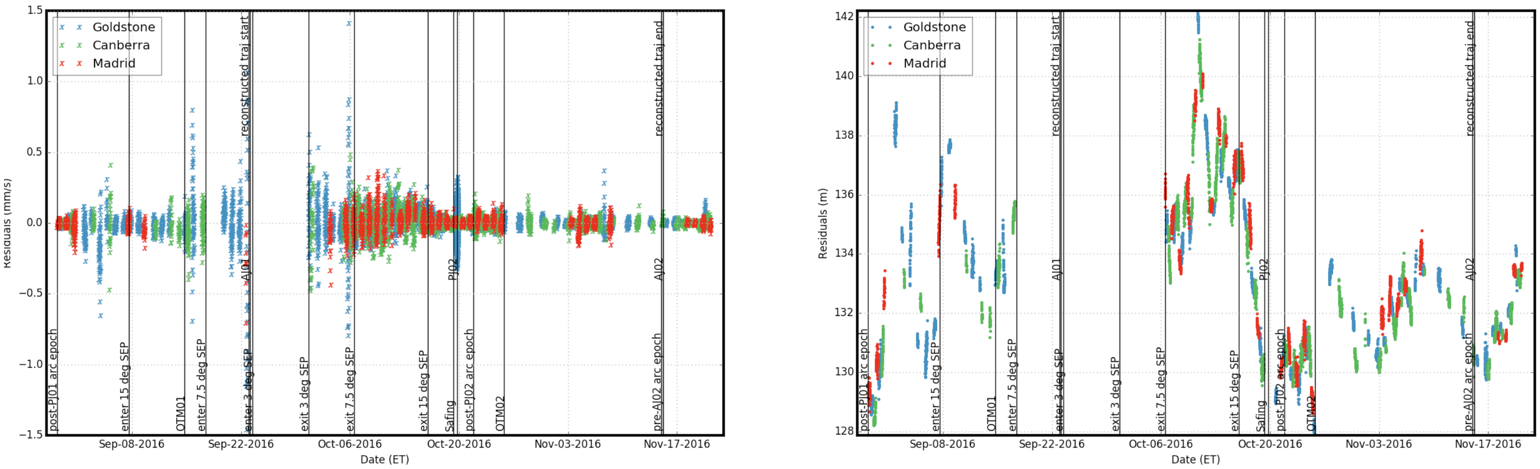

Figure 12. Doppler (right) and Range (left) Residuals During PJ02 Reconstruction Arc

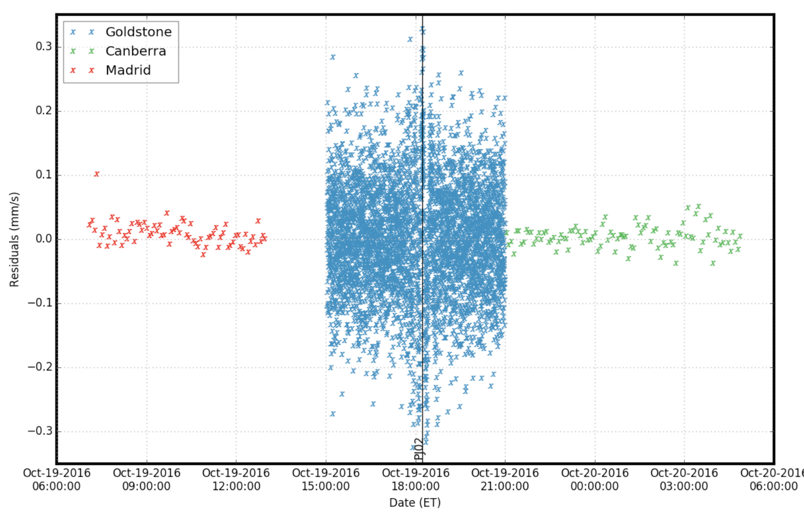

Figure 13. Doppler Residuals around PJ02 Encounter

PJ03

Originally PJ03 was designated for the execution of the PRM-cleanup maneuver. The cancellation of PRM, the loss of the science opportunity at PJ02, and engineering activities required to recover the spacecraft from safe mode resulted in a substantial redesign of the reference trajectory.[6] As such, OTM02 was delayed and optimized to target a new PJ03 equator-crossing longitude, which was now repurposed to be a "GRAV perijove." OTM02 executed nominally and the OD solutions were sufficiently stable to cancel the statistical cleanup maneuver, STM02.

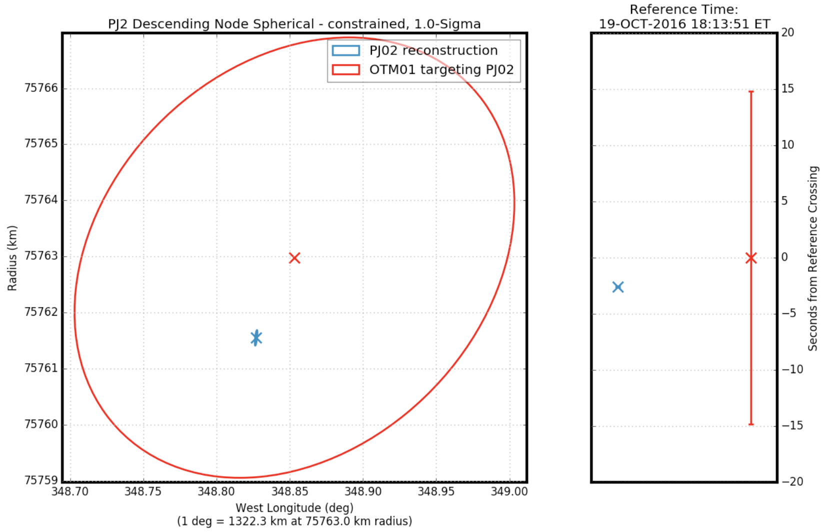

Figure 14. Results of Equator-Crossing from PJ02

The residuals for the 2-way Doppler and range measurements for the entire data arc relative to the reconstructed trajectory are shown in Figure 16, with Figure 17 zooming in to show the Doppler residuals around PJ03. This was the first perijove to follow the new nominal orbital operations timeline with the OTM targeting the next equator-crossing longitude at PJ04 occurring 7.5 hours after PJ03.

The same gravity model used for the reconstruction of PJ02 was used for PJ03 and again stochastic accelerations were used to account for unmodeled higher order zonal harmonics in Jupiter's gravity. Even with stochastic accelerations, the Doppler data for about 60 minutes on either side PJ03 did not fit as well as the data further from perijove. This relatively poor fit indicated that the mismodeling was not due to dynamics, but some other cause. After the reconstruction was delivered, the Radio Science team had concluded that uncalibrated media effects due to the Io plasma torus were the reason for the signal in the Doppler data around perijove.[14]

Figure 17 presents the OD team's reconstruction of PJ03 (blue ellipse) relative to the targeting maneuver (red ellipse) and relative to the decision to cancel the statistical cleanup maneuver (green ellipse). The uncertainty in the radius direction of STM02 was larger than expected from the OTM02 maneuver execution error model. Analysis showed that this uncertainty inflation was caused by the considered uncertainty in Earth's polar motion, Jupiter's pole, and Jupiter's gravity.

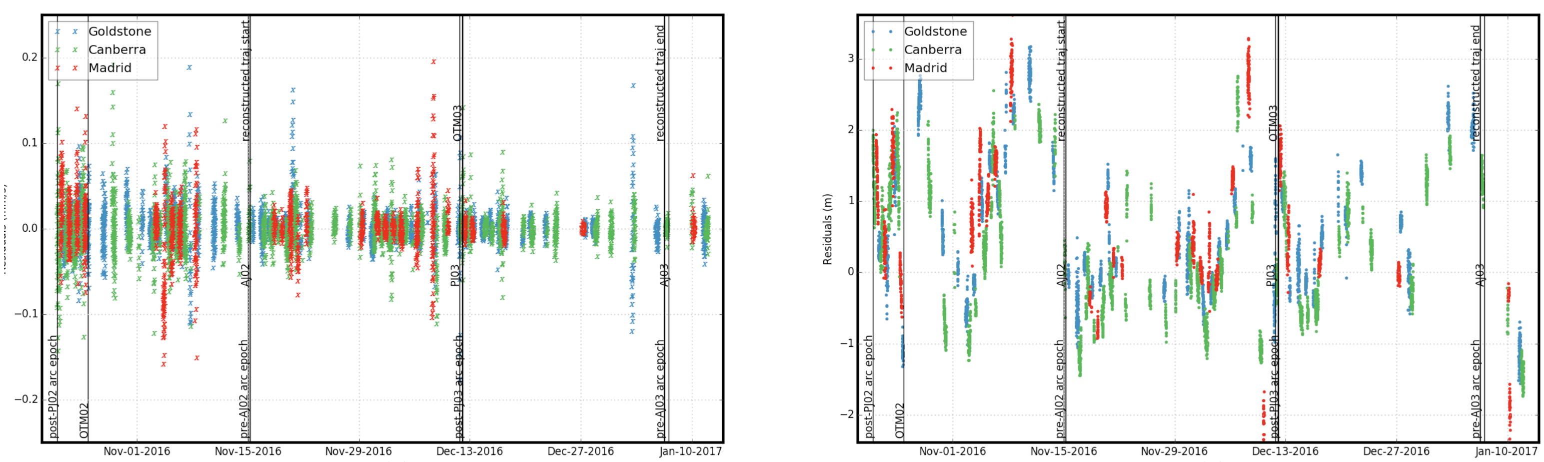

Figure 15. Doppler (right) and Range (left) Residuals During PJ03 Reconstruction Arc

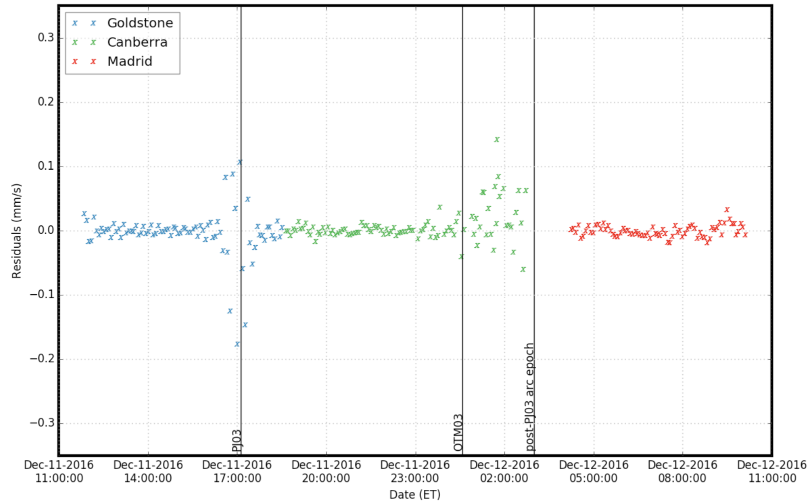

Figure 16. Doppler Residuals around PJ03 and OTM03

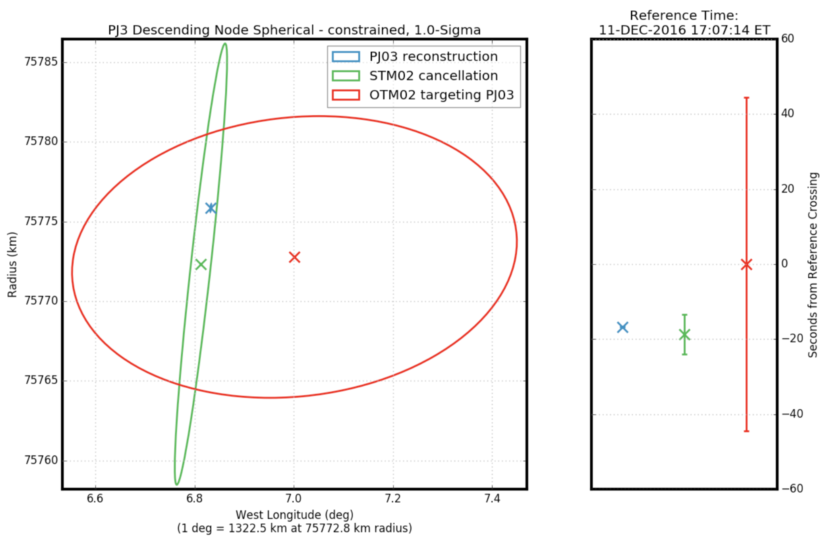

Figure 17. Results of Equator-Crossing from PJ03

PJ04

The PJ04 encounter was the first "MWR perijove" where the spacecraft was turned 24-degrees away from Earth in order to align the Juno's spin-plane along the nadir direction of Jupiter. Having the spacecraft pointed this far away from Earth required use of the MGA. For the first time in three years the despin tool was required to remove a significant spin signature as well as account for the spin-induced Doppler bias. But PJ04 showed us the limitations of the despin tool. The software was developed with two assumptions: the spin rate and the attitude would always be nearly constant during the interval being despin.

Due to torques acting upon the spacecraft from the spacecraft travelling in a strong magnetic field, the spin rate noticeably changed during a perijove flyby. Furthermore, due to gravity torques the attitude noticeably changed. During a couple of hours centered at PJ04, the spin rate changed about -0.0025 deg/s (about -3e-07 deg/s^2) and the attitude changed about 0.001 degrees over a couple of hours (see Figure 18). This change in spin rate during PJ04 was three orders of magnitude larger than what the OD team observed during interplanetary cruise where SRP was changing the spin rate. For perijove passes that used the HGA, this change in spin rate can be neglected because the resulting change in the spin-induced Doppler bias is well below the noise level of the Doppler data. This more rapid change in the spin rate on the MGA resulted in the inability of the despin tool to determine a valid spin state during PJ04. The OD team's work-around was to chop up the tracking pass into shorter intervals and despin the Doppler data piecewise throughout the entire perijove tracking-pass.

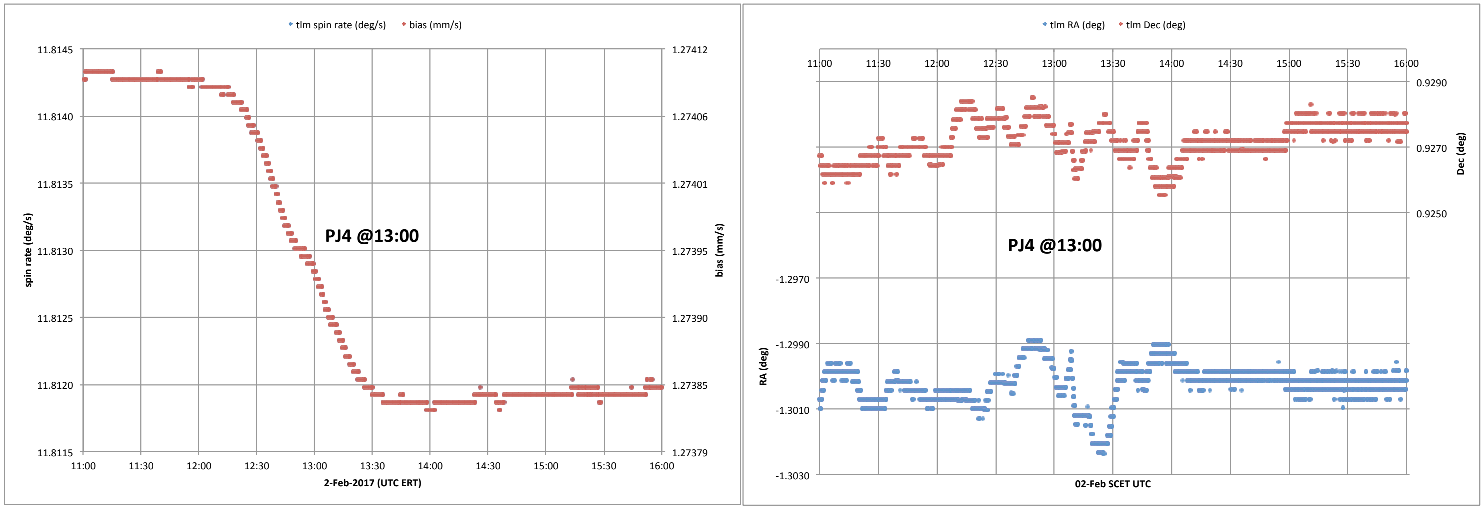

Figure 18. Telemetry of Juno Spin Rate (right) and Attitude (left) During PJ04

Knowing precisely when to begin and end these intervals involved retrieving and analyzing spacecraft telemetry to reconstruct the spin rate. It is routine for the OD team to query telemetry to receive details of small forces events. Of specific interested included when these events executed, the nature of the event (spacecraft turn, either to or away from Earth; spin-rate control; and nutation damping) and the resulting attitude at the end of the small force event.

Even though this extra telemetry analysis gave a much more reasonable spin rate by which the spin-induced Doppler bias could be properly removed, there was still some residual signal in the Doppler data indicating that the total spin state was not quite correct. Due to this residual signal, the data was not compressed in order to avoid the signal to be aliased due to compression.

Due to station issues at the Goldstone DSN complex, a 2-way Doppler link was not established with the spacecraft during the perijove track. But since the Canberra complex had on overlapping view-period, 3-way Doppler data with the uplink from Goldstone and the downlink from Canberra was available quite near to perijove. This was the OD team's first use of 3-way Doppler data during a perijove pass.

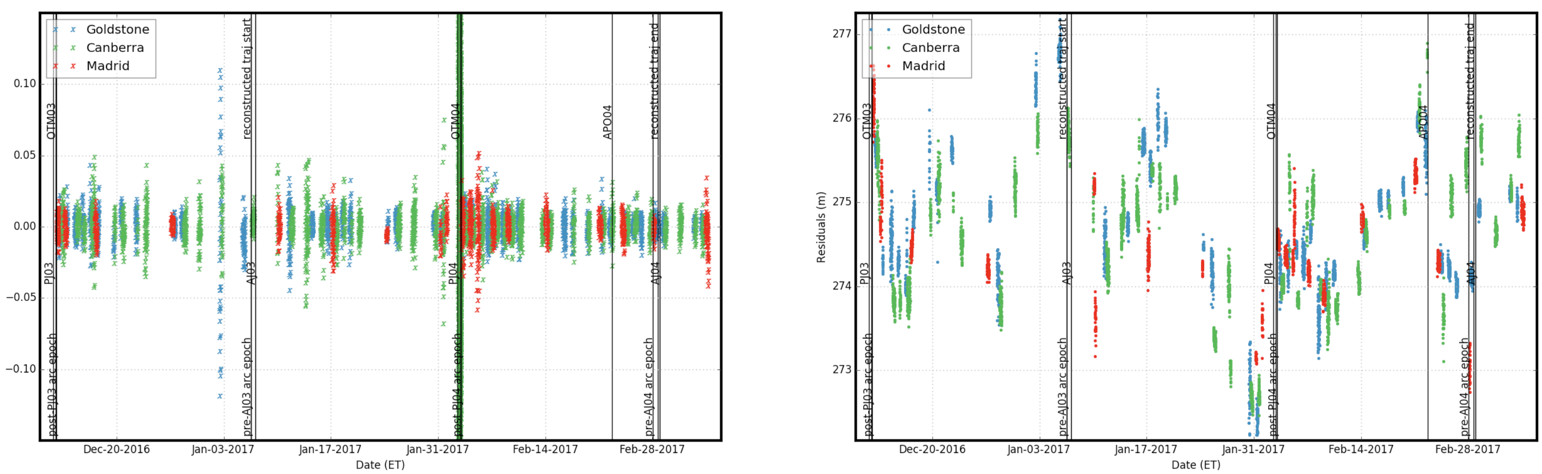

Figure 19. Doppler (right) and Range (left) Residuals During PJ04 Reconstruction Arc

The residuals for the 2-way Doppler and range measurements for the entire data arc are shown in Figure 19, with Figure 20 zooming in to show the Doppler residuals around PJ04. The grey points in Figure 20 are data that were ignored and they are not part of the fit. We chose to ignore this data because we believe it showed a signal due to uncalibrated media effects caused by to the Io plasma torus (similar to signatures seen at PJ02 and PJ03). It is worth noting how the MGA Doppler data becomes less noisy once the Juno is turned back toward Earth. The data gets even less noisy when Juno returns to the HGA after OTM04. As previously mentioned, when pointed directly at Earth there is no discernable spin signature to be removed and only the spin-induced Doppler bias needs to be accounted for by the despin tool.

Figure 21 presents the OD team's reconstruction of PJ04 (blue ellipse) relative to the targeting maneuver (red ellipse) and relative to the decision to cancel the statistical cleanup maneuver (green ellipse).

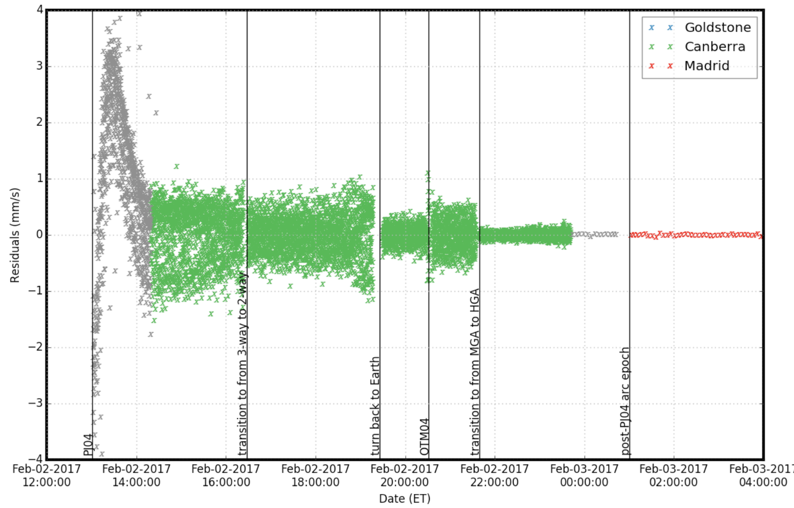

Figure 20. Doppler Residuals around PJ04 and OTM04
(note: residual points in grey are ignored points and not a part of the fit)

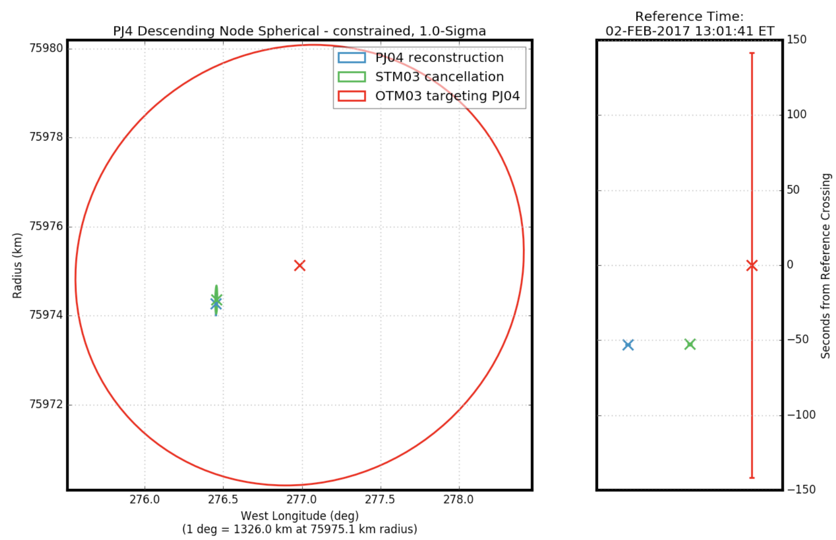

Figure 21. Results of Equator-Crossing from PJ04

PJ05

PJ05 was Juno's second consecutive "MWR perijove." After PJ04, the OD team developed an alternate method to removed the spin signature of the off-Earth MGA Doppler data similar to how the Radio Science team despins Doppler data. This alternative technique to despin Doppler data uses reconstructed spacecraft attitude from the Guidance, Navigation, and Control (GNC) team to only estimate the antenna offset in the XY-plane of the spacecraft in order to remove the spin signature. Following that the time-varying spin rate reconstructed by GNC is used to remove the spin-induced Doppler bias. This process is more robust to the changing spin rates and attitudes. The OD team intends to use this procedure as the standard procedure for all future MWR perijove passes.

The residuals for the 2-way Doppler and range measurements for the entire data arc are shown in Figure 22, with Figure 23 zooming in to show the Doppler residuals around PJ05. Two-way Doppler data was received throughout the entire DSN track over the Goldstone complex. Again, the data were not compressed in order to mitigate aliasing of the Doppler data through compression. Some effect of the Io plasma torus is seen in the Doppler data around perijove, where the residuals do not quite fit flat. This perijove was the first reconstruction that did not need to employ stochastic accelerations. The Doppler data fit very well with the same gravity model provided by the Radio Science team that we used in other recent reconstructions.

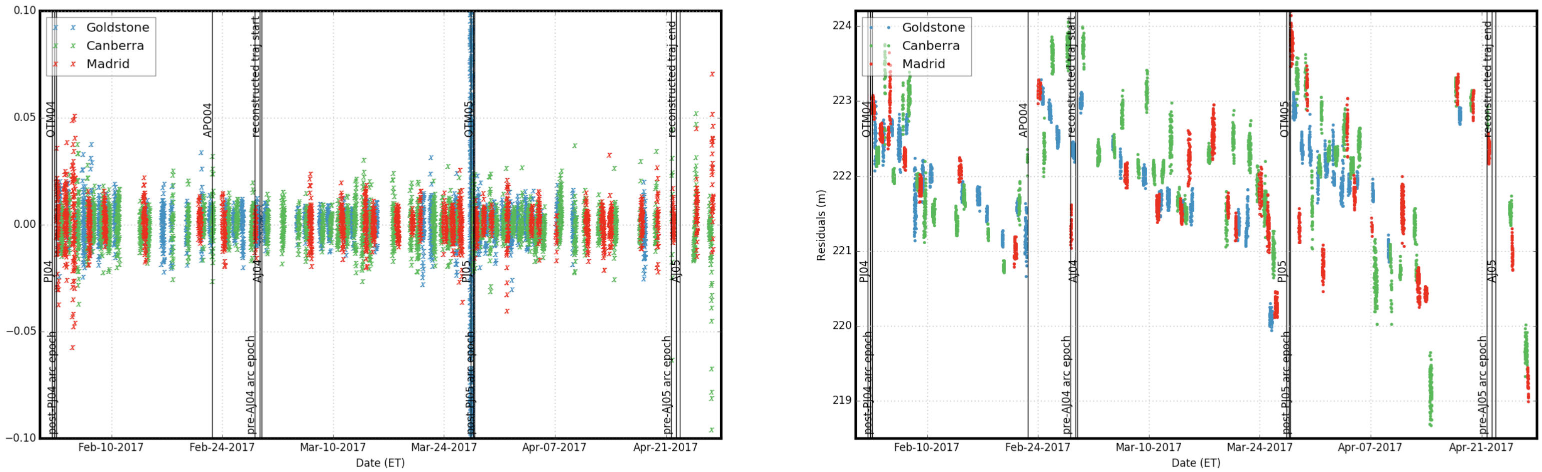

Figure 22. Doppler (right) and Range (left) Residuals During PJ05 Reconstruction Arc

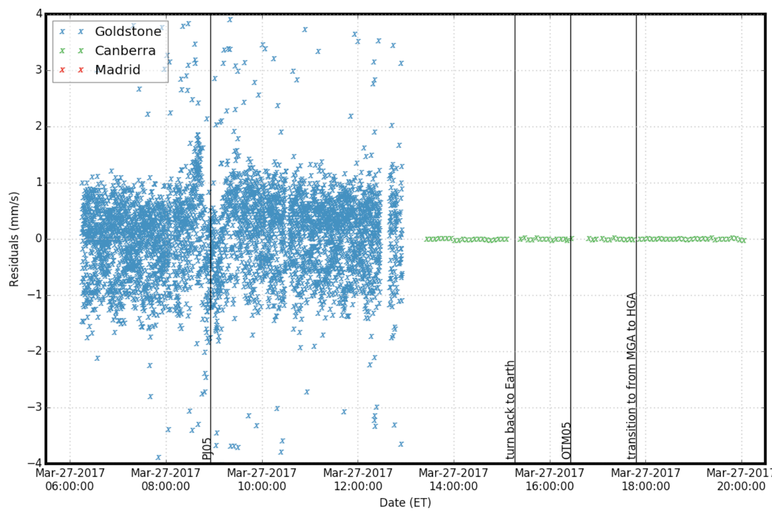

Figure 23. Doppler Residuals around PJ05 and OTM05

Figure 24 presents the OD team's reconstruction of PJ05 (blue ellipse) relative to the targeting maneuver (red ellipse) and relative to the decision to cancel the statistical cleanup maneuver (green ellipse).

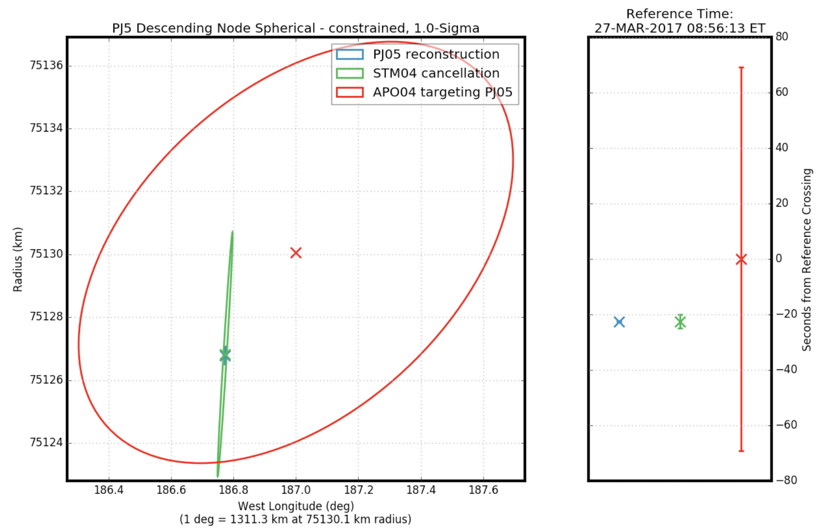

Figure 24. Results of Equator-Crossing from PJ05

PJ06

PJ06 was the first "GRAV perijove" since PJ03. The residuals for the 2-way Doppler and range measurements for the entire data arc are shown in Figure 25, with Figure 26 zooming in to show the Doppler residuals around PJ06. This perijove was performed using the HGA and "despinning" the raw Doppler data proceeded without any issues. An updated gravity model was delivered by the Radio Science team after PJ05. No stochastic accelerations were required and the Doppler data around the time of the Io plasma torus was ignored. Note that Figures 17, 20, and 22 are all displayed using the same scale on the vertical axis for better comparison of the MGA perijove data relative to the HGA data. Figure 27 presents the OD team's reconstruction of PJ05 (blue ellipse) relative to the targeting maneuver (red ellipse) and relative to the decision to cancel the statistical cleanup maneuver (green ellipse).

SUMMARY

Juno's first year orbiting Jupiter was expected to be full of surprises from a scientific discovery point of view, but it turned out to be equally as exciting from a spacecraft and navigation perspective. Despite the Navigation team's best-laid plans and all the testing of procedures and scripts, the cancelation of PRM necessitated an overhaul of the processes and architecture, not just by the Orbit Determination team, but also the Trajectory Design team and Maneuver team.[6,13]

All in all, it has been a very successful first year for the Juno Navigation team. All the longitudes of the equator crossings were within a half-degree or better of the targets, all OTM and APO maneuvers executed nominally, and all statistical maneuvers that could be canceled were canceled. The OD team's collaborative relationship with the Solar System Dynamics group and Radio Science team has allowed us to improve trajectory reconstructions with a better Jupiter barycenter ephemeris, gravity field and pole. Also the OD Team enhanced their capability to despin the raw Doppler using high-rate data of the spacecraft's spin rate and attitude during perijove.

We look forward to Juno continuing on its journey orbiting Jupiter for at least another year and are confident that the mission will be extended to complete the orbital net around Jupiter collecting valuable science data, taking unprecedented images of iconic features like the Great Red Spot, enhancing our understanding of our solar system and our universe, and ultimately rewriting the textbooks.

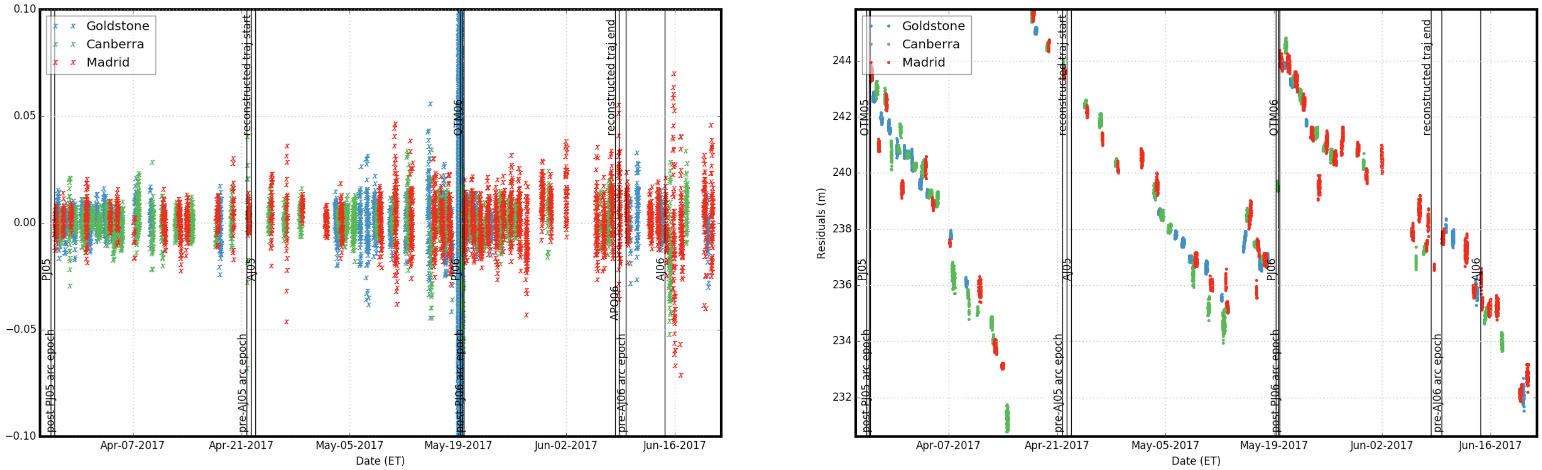

Figure 25. Doppler (right) and Range (left) Residuals During PJ06 Reconstruction Arc

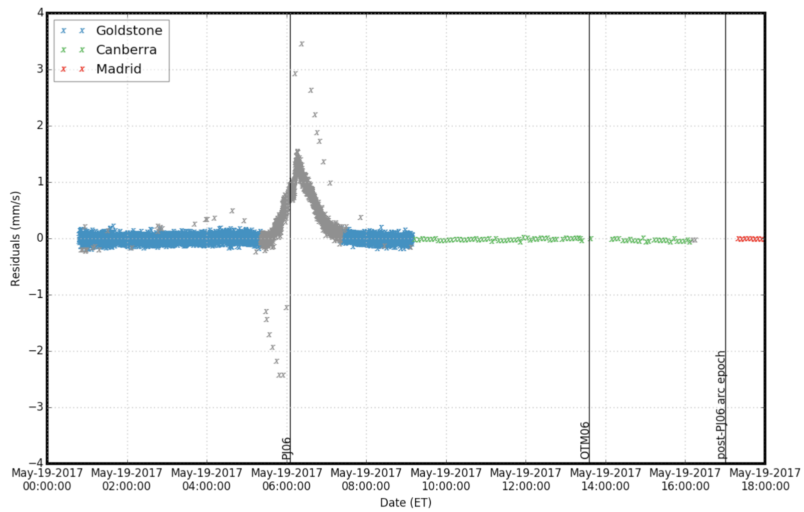

Figure 26. Doppler Residuals around PJ06 and OTM06
(note: residual points in grey are ignored points and not a part of the fit)

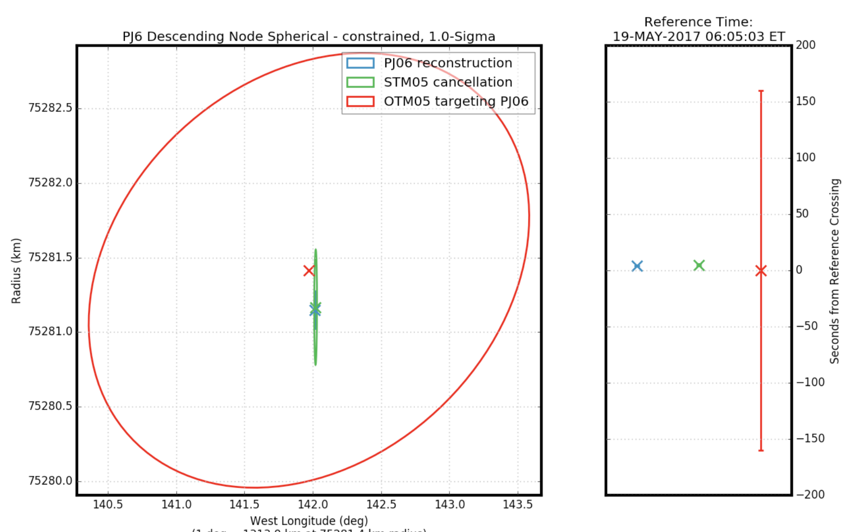

Figure 27. Results of Equator-Crossing from PJ06

ACKNOWLEDGMENTS

This work presented in this paper was performed by the Juno Orbit Determination Team along side with the Maneuver and Trajectory Design teams. Special acknowledgement and thanks must be offered to the Solar System Dynamics group and Radio Science team at JPL for the guidance and product deliveries. All work was carried at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Government sponsorship acknowledged.

APPENDIX: TARGET VS. RECONSTRUCTED TRAJECTORY RESULTS WITH 1-SIGMA ERROR STATISTICS FROM PJ01 TO PJ06

				1-sigma error		
	Equator Crossing Time (ET)	Radius (km)	West Longitude (deg)	ECT (s)	R (km)	W.Lon (deg)
PJ01Target	27-Aug-2016 12:53:53.9	75720.41	97.00	93.45	19.69	0.94
PJ01 Recon	27-Aug-2016 12:53:18.6	75713.11	96.64	0.03	0.15	<0.001
error	35.3 s	7.30	0.36			
PJ02Target	19-Oct-2016 18:13:52.0	75762.98	348.85	14.84	3.93	0.15
PJ02 Recon	19-Oct-2016 18:13:49.4	75761.55	348.83	0.07	0.14	<0.001
error	2.6 s	1.43	0.02			
PJ03Target	11-Dec-2016 17:07:14.7	75772.77	7.00	50.22	9.40	0.51
PJ03 Recon	11-Dec-2016 17:06:58.0	75775.86	6.83	0.08	0.23	<0.001
error	16.7 s	-3.09	0.17			
PJ04Target	02-Feb-2017 13:01:42.0	75975.13	276.99	141.59	4.95	1.43
PJ04 Recon	02-Feb-2017 13:00:49.1	75974.27	276.45	0.08	0.29	<0.001
error	52.9 s	0.86	0.54			
PJ05Target	27-Mar-2017 08:56:13.3	75130.06	187.00	69.10	6.70	0.70
PJ05 Recon	27-Mar-2017 08:55:50.8	75126.78	186.77	0.08	0.31	0.001
error	22.5 s	3.28	0.23			
PJ06Target	19-May-2017 06:05:03.6	75281.41	141.97	159.95	1.46	1.61
PJ06 Recon	19-May-2017 06:05:07.9	75281.15	142.02	0.04	0.13	<0.001
error	-4.3 s	0.26	-0.05			

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